AMERICAN JOURNAL OF PHYSICAL ANTHROPOLOGY 109:501–508 (1999)

Univariate Estimates of Sexual Dimorphism: The Effects of Intrasexual Variability

ELISABETTA MARINI,[1]* WALTER RACUGNO,[2] AND
SILVANA M. BORGOGNINI TARLI[3]
[1]*Sezione di Scienze Antropologiche, Dipartimento Biologia Sperimentale, Università di Cagliari, Cittadella Universitaria di Monserrato, 09042 Monserrato, (Cagliari), Italy*
[2]*Dipartimento di Matematica, Università di Cagliari, 09124 Cagliari, Italy*
[3]*Sezione di Antropologia, Dipartimento di Etologia, Ecologia, Evoluzione, Università di Pisa, 56126 Pisa, Italy*

KEY WORDS dimorphism variations; methods; statistical indices

ABSTRACT The difference between male and female values of quantitative traits depends on the distribution of the variables within each sex, increasing with the rise in the difference between male and female average values and with the decrease of the dispersion of measurements in both sexes.

This paper deals with the sensitivity of some widely used indices (relative difference between male and female mean values (*MDI*), Student's *t*, and the so-called Bennett-Chakraborty-Majumder *D* coefficient) with respect to intrasexual variability. The Kolmogorov-Smirnov distance (*KS*) is suggested here as a further index of dimorphism, although it is not usually utilized for this purpose.

The theoretical approach is accompanied by the analysis of empirical data (metric variables obtained from a sample of present Sardinians) and by computer simulations under various assumptions.

Indices based on the difference between male and female average values are not able to evaluate fully the various aspects of dimorphism. Student's t proved to be an adequate measure of whole sex differences, both in real and in simulated samples, as intrasexual variability is included in its formulation. The *D* index also proved to be a good measure of undivided sexual dimorphism, as it is the result of formal examination, and from application to empirical or to simulated cases.

The Kolmogorov-Smirnov distance gave the best performance both in formal examination and in the whole simulation results, as it takes into account intrasexual variability, and is applicable to any kind of distribution. In simulated cases it was sensitive to variations of means and variances, and it was able to evaluate variance dimorphism.

Since the last three indices measure the combined effect of size and variance dimorphism, the joint use of the *MDI* index is suggested in order to isolate the relative contribution of the difference between the means. Am J Phys Anthropol 109:501–508, 1999.

In the study of sexual dimorphism, intrasexual variability has only recently received some consideration (Meindl et al., 1985; Tague, 1989, 1991, 1992, 1995; LaVelle, 1993, 1995; Plavcan, 1994), in spite of the fact that such variability influences the manifestation of dimorphism and its interpretation.

Grant sponsor: M.U.R.S.T. 60%.

*Correspondence to: Elisabetta Marini, Sezione di Scienze Antropologiche, Dipartimento Biologia Sperimentale, Università di Cagliari, Cittadella Universitaria di Monserrato, SS 554, Km 4500, 09042 Monserrato (Cagliari), Italy. E-mail: emarini@unica.it

Received 20 March 1997; accepted 2 April 1999.

Intrasexual variability can affect significantly the reliability of the measurement of sex differences. The discrimination between male and female values of quantitative traits depends on the distribution of variables within each sex, increasing with the rise in the difference between male and female average values and with the decrease of the dispersion of measurements in both sexes.

Intrasexual variability needs to be considered when choosing traits to be used as sex indicators in recent skeletal or fossil samples. For example, a "diagnostic" trait of the pelvis, the shape of the sciatic notch (Sauter and Privat, 1952), in spite of its significant sexual dimorphism in terms of distance between average values, has such a great overlap between male and female distributions that its effectiveness in sex diagnosis is strongly reduced (Holcomb and Konigsberg, 1995). Comparison of the magnitude of sexual dimorphism in various samples or populations has to consider possible differences in degrees of dimorphism, either because of different distances between mean values or, even in case of equal distances, because of a differing extent of intrasexual variability.

Accordingly, sexual dimorphism can be regarded as a compound of the differences in location (or mean dimorphism) and in dispersion (or variance dimorphism, i.e., sex differences in the extent of variability of a given trait). Sex differences in variability are well-known, with females less variable or more "canalized" than males with respect to size dimorphism. Reduced variability of females could be the consequence of natural selection favoring optimal dimensions given extra nutritional demands during pregnancy and lactation, especially in instances of fluctuating resources (Stini, 1982; Wolfe and Gray, 1982). Although this hypothesis seems theoretically sound, some stronger support from empirical data is required, beginning with the examination of differences in intrasexual variability.

Unfortunately, at least among physical anthropologists, the most popular indices used to quantify sexual dimorphism are based on ratios or differences between male and female mean values, without a consideration of dispersion parameters. An updated review of many indices among such techniques can be found in Lovich and Gibbons (1992).

The present paper shows the effects of intrasexual variability on the degree of sexual dimorphism, using empirical data (somatic measurements on extant Sardinians), formal comparisons, and computer simulations to evaluate the performance of three univariate indices of dimorphism widely used in the anthropological literature: the mean distance index (*MDI*), the Student's *t*, and the so-called *D* index of Bennett-Chakraborty-Majumder (Bennett, 1981; Chakraborty and Majunder, 1982). Univariate indices are considered here, since their simplicity of application permits comparisons with cases from the literature where only summary statistics are available, and because of their widespread use in physical anthropology. A further index, the Kolmogorov-Smirnov distance (*KS*), is tested and proposed as the most suitable to measure sexual dimorphism in its general meaning (mean and variance). Finally, a way to evaluate the relative contribution of mean and variance to sex dimorphism is suggested.

MATERIALS AND METHODS

A sample of modern Sardinians, aged between 21–50 years and coming from central and southern regions of the island, underwent anthropometric investigation. For each subject, 48 somatic and cephalic variables, including heights, diameters, perimeters, and skinfold thickness, were taken following the methods of Weiner and Lourie (1981) (see Appendix).

Intrasexual variability was measured as the standard deviation.

Three indices of dimorphism were examined:

$$MDI = \frac{\bar{x}_m - \bar{x}_f}{\bar{x}_m} \cdot 100, \qquad (1)$$

based on the distance between male and female means, $\bar{x}_m$ and $\bar{x}_f$ respectively, weighted on the male mean (Hall, 1982).

Student's t, which weighs the same distance by an average measure of variability, is:

$$t = \frac{\overline{x}_m - \overline{x}_f}{s\left(\frac{1}{n_m} + \frac{1}{n_f}\right)^{1/2}} \tag{2}$$

$$\text{with} \quad s^2 = \frac{(n_m - 1)\, s_m^2 + (n_f - 1)\, s_f^2}{n_m + n_f - 2},$$

where n_m and n_f are the male and female sample size and s_m^2, s_f^2, are the corresponding variances.

The index of Bennett (1981) as corrected by Chakraborty and Majumder (1982), based on the measure of the nonoverlapping area of male and female distributions, and according to the formulation by Inman and Bradley (1989), is:

$$\begin{aligned} 2D = 2|F(x_B|\overline{x}_f, s_f^2) - F(x_A|\overline{x}_f, s_f^2) \\ + F(x_A|\overline{x}_m, s_m^2) - F(x_B|\overline{x}_m, s_m^2)], \end{aligned} \tag{3}$$

where $F(s_A|\cdot,\cdot)$ and $F(s_B|\cdot,\cdot)$ denote the normal cumulative functions with mean and variance equal to the mean and variance of the male and female samples, calculated at the intersection points x_A and x_B, respectively, with $x_A < x_B$. Under the assumption of homoscedasticity, Equation (3) becomes:

$$2D = 2\,[F(x_0|\overline{x}_f, s^2) - F(x_0|\overline{x}_m, s^2)],$$

where x_0 indicates the only intersection point.

The indices were first examined by analyzing the parametric correlation (Pearson's r) among them, in the 48 variables, and by evaluating their concordance with a predicted trend of degrees of dimorphism (Table 1). The relation between indices and intrasexual variability is shown in Figure 1.

The KS index (Kolmogorov, 1933; Smirnov, 1939) was also considered:

$$KS = \sup_x |\, S_{n_m}(x) - S_{n_f}(x)\,|, \tag{4}$$

where S_{n_m} and S_{n_f} indicate empirical cumulative functions of male and female samples, respectively.

KS, which is not usually applied to actual data, is nevertheless proposed here as another index of dimorphism. Its comparative suitability is discussed through the formal examination of the four indices.

TABLE 1. Values of D, t, *and* MDI *for some anthropometric measurements with predicted increasing degree of sexual dimorphism (empirical data from present Sardinians)*[1]

Anthropometric variables	*D*	*t*	*MDI*
Dactylion height	0.40	16.48	5.76
Body weight	0.58	30.88	21.14
Sitting height	0.50	26.10	5.75
Cephalic length	0.62	34.21	5.67
Upper arm circumference (contracted, right side)	0.62	32.78	15.74
Biepicondylar humerus (right side)	0.81	47.70	12.86

[1] *MDI*, mean distance index; *t*, Student's *t*; *D*, index of Bennett-Chakraborty-Majumder.

Finally, the absolute and relative performance of the four indices in different situations (normal distributions with fixed means and variable variances under homoscedasticity, variable means and fixed variances under homoscedasticity, and fixed means and variable variances under heteroscedasticity) was evaluated by computer simulation.

RESULTS AND DISCUSSION

Effect of intrasexual variability on experimental data

The correlation coefficients between pairs of indices in the 48 anthropometric variables show a very good agreement between D and t: $r\,(D, |t|) = 0.98$, while there is a low correlation with MDI: $r\,(D, |MDI|) = 0.15$ and $r\,(|t|, |MDI|) = 0.05$.

Table 1 shows the values furnished by the three indices for some anthropometric variables for which the degree of dimorphism is expected to increase according to the literature. In particular, in the case of skeletal samples, bone circumferences and diameters show a greater degree of dimorphism than length measurements (Hamilton, 1982; Borgognini Tarli and Masali, 1983; Borgognini Tarli and Repetto, 1986a,b). In the sample of extant Sardinians, discriminant analysis (Marini, 1992) shows that the most dimorphic measurements are, in order of increasing index values, dactylion height, body weight, sitting height, cephalic length, upper arm circumference (contracted, right side), and biepicondylar humeral diameter (right side).

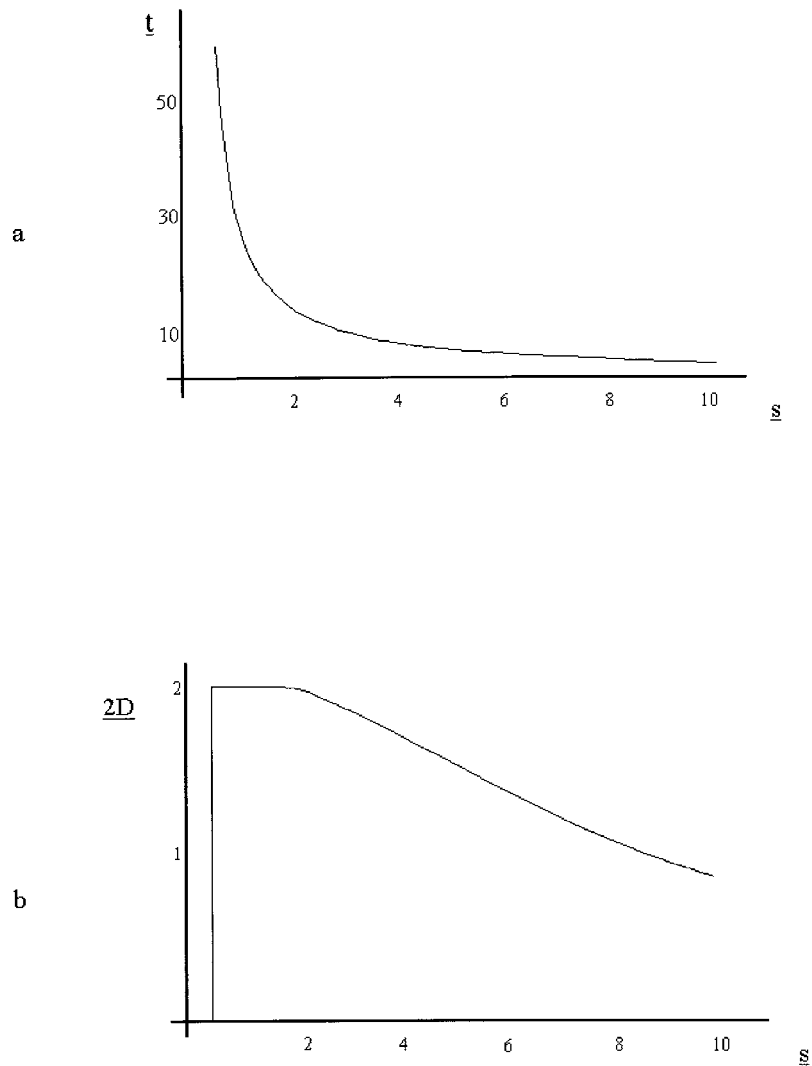

Fig. 1. Trend shown by indices *t* **(a)** and *2D* **(b)** with increasing average intrasexual standard deviation *s* in particular case of two given values of male and female average values (stature: $\bar{x}_m$=167.0, $\bar{x}_f$ = 154.6).

As can be seen, *D* and *t* values vary in the same way and in accordance with the predicted trend, while *MDI* shows unpredicted or no variations.

In order to examine the sensitivity of the indices to changes in variability, their values were plotted against the average value *s* of the standard deviation in both sexes.

Figure 1 shows the trend of *t* (Fig. 1a) and of *2D* (Fig. 1b) with intrasexual variability *s*, in the particular case of body height (male average stature $\bar{x}_m$ fixed to 167.0 cm and female average stature $\bar{x}_f$ fixed to 154.6 cm), as expressed by the graph of the formulae. Index *MDI* was not included given its lack of explicit relation with *s*.

The value of *t* decreases hyperbolically when *s* increases, but it shows greater variations for low values of *s*, while it remains almost constant in the higher range of *s* values.

The *D* index also has, on the whole, a negative correlation with intrasexual variability. A first linear horizontal trend, corresponding to the maximum degree of sexual dimorphism, with practically no overlap between male and female distributions ($s < 2$), is followed by a flex point towards a steady

negative slope. As compared with t, D shows a smoother slope, indicating greater stability with respect to the order of magnitude of s.

Formal examination of indices

The descriptive use of any of the considered indices, with the exception of D which, according to the original formulation, was calculated here in the normal case only, does not require probabilistic assumptions about male and female distributions.

In particular, it has to be noted that the formula of *MDI* does not include any dispersion parameter, while, in the most widely used formulation of t, dispersion is expressed as mean sample variance weighted on the two observed samples, as the condition of homoscedasticity is implicit. In the case of heteroscedasticity (Behrens-Fisher problem), it is possible to apply Welch's correction:

$$t' = \frac{\bar{x}_m - \bar{x}_f}{\left(\dfrac{s_m^2}{n_m} + \dfrac{s_f^2}{n_f}\right)^{1/2}}$$

Note that the t statistic is distributed according to Student's t law, with $v = n_m + n_f - 2$ degrees of freedom, while the t' is approximately distributed as t with

$$v = \left\{\left(\frac{s_m^2}{n_m} + \frac{s_f^2}{n_f}\right)^2 \middle/ \left[\frac{(s_m^2/n_m)^2}{n_m + 1} + \frac{(s_f^2/n_f)^2}{n_f + 1}\right]\right\}$$

The descriptive use of all the indices considered here applies to cases that seek to compare degrees of dimorphism among samples with different characteristics, e.g., differing dates or provenience, without estimating the significance of the differences observed. Otherwise, the inferential use of the same indices must take into account their probabilistic properties.

With the exception of *MDI*, which evaluates only the relative location of the samples, the index t requires the normality condition (in both cases of homo- and heteroscedasticity), while D requires the previous knowledge of the probabilistic model, and the Bennett and Chakraborty-Majumder applications refer to the normal case only. The *KS* index does not require any specific assumption about the shape of the distribution or the parameters, with the exception of the continuity of the distribution (a condition generally respected by anthropometric variables). Further, the two-sample Kolmogorov-Smirnov test is sensitive to any kind of difference between male and female distributions (location, dispersion, symmetry).

As already noted, variability is not considered in the *MDI* index, while in the case of Student's t, and of D and *KS* there is an inverse relation between standard deviation and degree of dimorphism.

Analysis of index behavior by computer simulation

In order to analyze the behavior of the four indices, we studied some simulated situations. Each trial was performed using 1,000 randomly generated samples from a normal distribution whose parameters μ and σ are of the same order of magnitude as $\bar{x}$ and s of stature values in present populations. In order to emphasize the different behaviors of the indices, a case with unrealistically high values of intrasexual variance and with very high difference between the means was also considered. The performances of the four indices were followed with fixed difference between the means and varying levels of variances, and with fixed variances and varying levels of the difference between the means in homoscedasticity, while in the heteroscedasticity condition, only the variances were allowed to move.

The main results of the simulation in the homoscedastic case are shown in Table 2, where the ranges of the results obtained in each trial are reported for the four indices together with the main trial conditions (first two columns).

As can be seen, *MDI* is insensitive to variations of intrasexual variability, except for a rise in its range, but it steadily increases with the difference between male and female mean values. The t, D, and *KS* indices increase both with the rise in the difference between male and female average values and with decrease of the variances.

Note that in case of proportional variation in the mean difference and in the variance (e.g., (5, 25) and (10, 100)), the values of t, $2D$, and *KS* remain virtually unchanged, as they are insensitive to variations in scale. Of course, such a situation was artificially produced to stress the effect of the variation of

*TABLE 2. Ranges of values of the four indices of dimorphism (*MDI, t, 2D*, and* KS*), obtained by simulation in the normal homoscedastic case*[1]

$\Delta\bar{x}$	Variance	*MDI*	*t*	*2D*	*KS*
10	25	4.8–6.9	5.60–9.13	1.17–1.59	0.64–0.80
10	100	3.9–7.9	2.34–5.11	0.51–1.07	0.34–0.54
10	225	2.9–8.7	1.15–3.69	0.24–0.83	0.22–0.44
5	25	2.0–4.1	2.31–5.14	0.59–0.97	0.34–0.56
10	25	4.8–6.9	5.60–9.13	1.17–1.59	0.64–0.80
20	25	10.2–12.1	12.54–17.13	1.84–1.97	0.94–1.00

[1] $\Delta\bar{x}$, difference between male and female average values; variance, intrasexual variance; *MDI*, *t*, and *D* as in Table 1; *KS*, Kolmogorov-Smirnov distance.

TABLE 3. Comparison between t *and* KS *in case of homo- (mean variance) and heteroscedasticity, with similar variances (as in the case of actual stature data) and very different variances (as in the fictitious example)*[1]

Variance	*t*	*KS*
Actual stature data		
$V_m = V_f = 39.47$	8.46–11.55	0.64–0.80
$V_m = 45.02$, $V_f = 33.99$	8.44–11.66	0.64–0.80
Fictitious data		
$V_m = V_f = 124.34$	4.20–7.11	0.38–0.58
$V_m = 225$, $V_f = 25$	4.24–7.20	0.50–0.70

[1] V_m, variance of males; V_f, variance of females; *t* and *KS*, as in Table 2.

the two kind of parameters (position and dispersion), but should seldom be encountered when examining real data. More generally, since *t*, *D*, and *KS* evaluate overall dimorphism, their values are not directly interpretable in terms of relative contribution of the distance between the two mean values or of the overlap due to dispersion of the two distributions. An indirect way to separate the two aspects can be furnished by the joint use of the *MDI* index. For instance, body weight and sitting height, both with a relatively high value of *D* and *t*, have a very different value of *MDI* (Table 1), indicating that the distance between the means is more effective on the dimorphism of the first trait, whose intrasexual standard deviation weighs, in fact, about twice as much (Appendix).

The comparison between the homoscedastic and the heteroscedastic case is reported in Table 3, where the simulation trials are limited to *t* (with Welch's correction in heteroschedasticity) and *KS*, since *MDI* was shown to be insensitive to the effects of variance and the behavior of *D* is predictably similar to that of *KS*. The first two rows refer to a real case (stature in the whole adult Sardinian sample), where male and female variances are very similar, while the other two rows refer to a fictitious sample with male variance much greater than female variance. The homoscedastic case was produced using the average variance for both sexes (first row in each pair). As can be noted, when male and female variances are similar, the two indices have a similar behavior in homo- and heteroscedasticity, but in the fictitious case with greater divergence between intrasexual variances, only the KS distance shows a marked increase in the heteroscedastic case, thus showing itself to be susceptible to the effects of variance dimorphism.

CONCLUSIONS

The effects of intrasexual variability on the degree of sexual dimorphism were shown using empirical data, formal comparisons, and computer simulations applied to four indices, each representative of a class of indices with a common theoretical basis and mathematical expression.

Indices based on the difference between male and female average values, however standardized, such as *MDI*, even if widely used in the literature (both for calculation convenience and for their apparent intuitiveness), are not able to wholly evaluate the various aspects of dimorphism. In fact, it was shown here that this index is not sensitive to the effects of variance, as could be predicted by its formulation, which does not contain any dispersion parameter. This was seen in applications to actual data (Table 1) and to simulated situations (Table 2).

Student's t proved to be an adequate measure of the overall degree of sexual dimorphism, as intrasexual variability is included in its formulation. It can also be utilized in the heteroscedastic case by applying the Welch's correction, but its inferential use is limited by the need to respect the normality condition. When employed on experimental

data (Fig. 1a), the *t* index showed the expected negative relation with intrasexual variability, although it was more sensitive to little variations of small variances than to huge variations of large variances. With simulated data, the *t* index appeared to be sensitive to variations of the mean differences and of the variances (Table 2). In the heteroscedastic case, it proved to be insensitive to variance dimorphism (Table 3).

The *D* index proved to be a good univariate measure of the combined aspects of sexual dimorphism, as it appeared from formal examination, and from application to empirical cases. In fact, it proved to be sensitive to the effects of variability and, as compared with Student's *t*, it showed a more regular trend and was not influenced by the order of magnitude of the standard deviation (Fig. 1b). In simulated cases the *D* index appeared to be sensitive to changes in variances and in mean differences (Table 2), on the whole behaving better than any of the indices examined so far.

The *KS* distance, proposed here as a further index of dimorphism, gave the best performance both in formal examination and in the whole simulation results. In fact, it takes into account intrasexual variability, and is applicable to any kind of continuous distribution. In simulated cases it proved to be almost equally sensitive to variations of mean differences and of variances (Table 2), and to be susceptible to the effects of variance dimorphism (Table 3).

In conclusion, intrasexual variability plays a significant role in the degree of sexual dimorphism. In general, a high variability corresponds to a low degree of dimorphism, and vice versa. Intrasexual variability can also be part of the differences between sexes, as it is the basis of variance dimorphism. Therefore, most of the indices widely used in anthropological research, such as *MDI*, although giving a point estimate of size dimorphism, are not able to evaluate the phenomenon in its wholeness, as they simply cut off one of the pervasive realities in biology, i.e., variability. We thus suggest that such indices are inadequate in the study of geographic, diachronic, and phyletic variations of dimorphism.

It is outside the scope of this paper to propose new instruments to separately measure the two aspects of sexual dimorphism, as it also is to propose that a further interfering factor, i.e., allometry, ought to be taken into account. At the present stage of research, using statistical tools that are currently available, differentiation between the two aspects of sex differences might be obtained by the combined application of two statistical tests. We recommend the linked use of *KS* and *MDI* indices in order to evaluate the relative contribution of the means, since the first test does not put conditions on the distribution of the data, and the second test gives a point estimate of the mean difference, which is reasonably independent from dimensionality.

ACKNOWLEDGMENTS

We thank the anonymous referees for their comments and observations, which contributed to substantial improvements of the paper.

APPENDIX. Summary statistics of the original empirical data[1]

Anthropometric variables	Males			Females		
	$\bar{x}_m$	s_m	N	$\bar{x}_f$	s_f	N
Body weight (kg)	71.9	10.30	751	56.7	8.80	762
Stature	167.0	6.71	754	154.6	5.83	764
Sitting height	87.0	3.91	752	82.0	3.54	763
Acromial height	135.6	5.68	511	126.2	5.24	532
Olecranon height	103.6	4.65	512	96.7	4.24	532
Stylion height	80.8	4.10	512	75.9	3.70	532
Dactylion height	62.5	3.81	511	58.9	3.23	532
Anterosuperior iliac spine height	97.9	5.21	512	91.3	4.64	531
Trocantherion height	82.3	4.81	733	76.5	4.31	741
Tibial height	46.7	2.79	512	43.4	2.76	533
Sphyrion height	6.7	0.97	511	6.2	0.86	532
Chest depth	20.8	2.32	751	17.3	2.25	762
Biacromial diameter	39.7	2.40	751	35.3	1.84	761
Biiliac diameter	28.0	1.91	749	27.2	2.16	762
Wrist breadth R	5.8	0.31	582	5.1	0.28	603
Wrist breadth L	5.7	0.31	567	5.0	0.28	584
Biepicondylar humerus R	7.0	0.36	662	6.1	0.33	677
Biepicondylar humerus L	6.9	0.39	661	6.0	0.33	676
Bimalleolar breadth R	7.4	0.47	581	6.6	0.39	605
Bimalleolar breadth L	7.3	0.47	566	6.5	0.38	583
Biepicondylar femur R	9.8	0.51	582	9.0	0.53	604
Biepicondylar femur L	9.7	0.49	567	8.9	0.51	584
Chest circumference	89.3	6.92	747	74.3	7.11	760
Waist circumference	83.8	9.48	749	70.3	9.17	760

(*Continued*)

APPENDIX. (Continued)

Anthropometric variables	Males $\bar{x}_m$	s_m	N	Females $\bar{x}_f$	s_f	N
Upper arm circumference (relaxed) R	28.4	2.67	693	25.3	2.82	705
Upper arm circumference (relaxed) L	27.8	2.58	659	24.9	2.77	670
Upper arm circumference (contracted) R	32.4	2.88	691	27.3	2.92	699
Upper arm circumference (contracted) L	31.4	2.88	658	26.6	2.87	665
Proximal thigh circumference	51.2	5.00	526	51.4	4.70	544
Maximum forearm circumference	27.3	2.28	511	23.5	1.88	528
Maximum calf circumference	35.1	2.89	509	33.2	2.68	527
Biceps skinfold (mm)	4.9	2.41	655	7.8	3.91	669
Triceps skinfold (mm)	8.3	3.54	753	15.3	6.02	763
Forearm skinfold (anterior) (mm)	4.3	1.99	563	7.2	3.35	585
Forearm skinfold (posterior) (mm)	4.3	1.45	561	7.0	3.23	584
Chest skinfold (mm)	5.4	4.42	562	5.7	4.27	583
Subscapular skinfold (mm)	13.4	5.45	751	15.4	6.73	762
Abdomen skinfold (mm)	20.3	9.47	563	17.5	8.55	584
Suprailiac skinfold (mm)	12.7	6.10	751	12.8	6.51	763
Vertical skinfold (mm)	17.7	8.82	511	17.9	7.81	527
Anterior thigh skinfold (mm)	13.1	6.25	638	25.4	8.24	658
Posterior thigh skinfold (mm)	13.9	7.99	509	25.0	8.84	530
Medial thigh skinfold (mm)	18.4	8.82	511	27.4	7.58	528
Medial calf skinfold (mm)	12.5	6.31	509	18.5	7.12	530
Cephalic length	19.4	0.66	753	18.3	0.59	762
Cephalic breadth	15.1	0.58	749	14.5	0.52	762
Bizygomatic diameter	13.1	0.74	700	12.4	0.67	706
Morphological face height	11.8	0.72	753	11.0	0.66	761

[1] R, right side; L, left side; $\bar{x}_m$, mean of males; $\bar{x}_f$, mean of females; S_m, standard deviation of males; S_f, standard deviation of females; N, sample size. Unless otherwise shown, measurements are in cm.

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